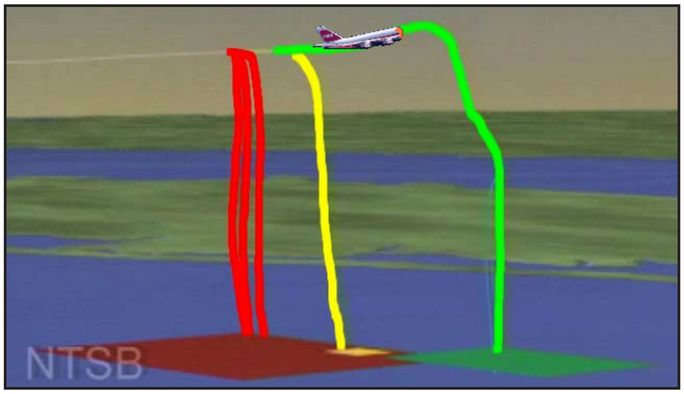

Figure 2: Red, Yellow, and Green Debris Fields

Fuel System

The Boeing 747-100 series uses Jet-A fuel from seven fuel tanks. Each wing contains three tanks. The lower fuselage holds a seventh tank, known as the center wing fuel tank (Figure 4). The CWT has a fuel capacity of 86,363 pounds, but whenever the six wing tanks hold sufficient fuel for a flight, the CWT only contains fuel remaining from the last flight, providing optimal spanwise wing load distribution. Ground crew personnel measured approximately 300 (about 50 gallons) pounds of fuel in the CWT prior to Flight 800's final takeoff. Under such conditions, the CWT ullage – the unfilled portion of the tank above the surface of the fuel – contains a mixture of fuel molecules and air whose combustibility depends upon its fuel-air ratio, temperature, and pressure. The aircraft's three air-conditioning packs, which could radiate heat at up to 350 degrees F, rested in an uninsulated, unvented compartment just inches beneath the CWT's aluminum floor. The tank and ullage absorbed heat from the packs for 2 ½ hours on the ground. Testing found that a near-empty center tank heats quickly, speeding fuel evaporation and increasing the flammability of the ullage. Additionally, increasing altitude as the airplane climbed lowered the air pressure, reducing the temperature needed to ignite the fuel/air mixture. (Figure 3 illustrates the flammability envelope for Jet-A fuel.)

Fuel System Wiring

The Fuel Quantity Indication System (FQIS) includes probes and compensators connected in series inside each fuel tank. The system measures capacitance values inside each tank and uses those values to calculate the total amount of fuel on the aircraft. Wiring within the fuel tanks is silver-plated copper that is insulated with Teflon. Wires routed between the tank entrance and the flight deck were insulated with an aromatic polyimide, known as Poly-X (BMS13-42A). The CWT also contained a junction block for wiring routed to each of the other fuel tanks.

The minimum ignition energy for hydrocarbon fuels is 0.25 millijoules (mJ). To keep the vapor in the tank from igniting, the power supplied to FQIS wiring was intended to have a limit of 0.02 mJ, which would be extremely low when compared to other B-747 systems. The FQIS wiring runs from the fuel tanks to the flight deck along raceways shared with wiring from other systems such as the cockpit voice recorder (CVR), fuel flow meter, and cabin lights. Such circuits carry much higher voltages and energies than allowed in the FQIS. For example, some cabin lights operate at up to 350 VAC at 400 hertz. FQIS wires co-routed with these other wires in large bundles were found tightly bound together, so that a chafe or cut could affect more than one wire (see Figure 4).

PROBABLE CAUSE

After an exhaustive investigation, the NTSB determined that "the probable cause of the TWA flight 800 accident was an explosion of the center wing fuel tank, resulting from ignition of the flammable fuel/air mixture in the tank." The source of ignition energy for the explosion could not be determined with certainty, but, of the sources evaluated by the investigation, the most likely was a short circuit outside of the CWT that allowed excessive voltage to enter it through electrical wiring associated with the fuel quantity indication system. Contributing to the accident was a design and certification concept that fuel tank explosions could be prevented solely by precluding all ignition sources. The design and certification of the Boeing 747 with heat sources located beneath the CWT without means to reduce the heat transferred into the CWT or to render the fuel vapor in the tank nonflammable also contributed to the accident.

Because FQIS wires are the only wires to enter the CWT and because they are co-routed within wire bundles containing circuitry from higher-voltage systems, investigators theorized that a high-voltage circuit contacted FQIS wires due to chafed, frayed, or otherwise damaged conditions. Once this higher voltage passed through FQIS wires to the FQIS probes inside the CWT, a latent fault on the probes, such as silver sulfide deposits, may have caused an electrical arc and subsequent tank explosion.

The CVR had recorded dropouts in the background electrical noise immediately preceding the explosion, which were indications that a short circuit had been affecting the energy in the electrical system intermittently. Further, the captain's comment concerning unusual behavior of the #4 engine fuel flow meter led investigators to focus on the wire routes used for the fuel flow meter system. Since wires for the fuel flow meters share a bundle with FQIS wires, NTSB theorized the captain's "crazy fuel flow" observation might actually have been a short circuit from the fuel flow meter wire to the FQIS

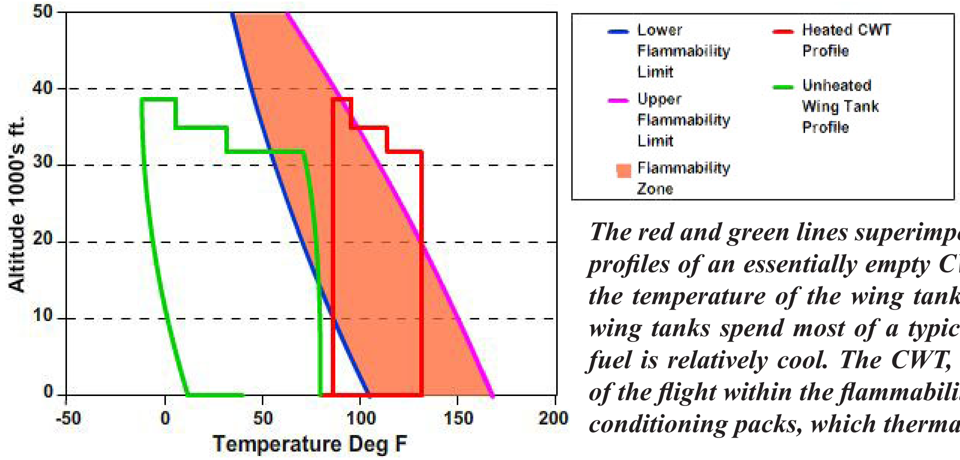

Figure 3: Flammability envelope for Jet A fuel. To the left of the blue line, the vapor is too lean to support combustion. To the right of the pink line, the vapor is too rich to support combustion.

The red and green lines superimposed upon the graph represent hypothetical flight profiles of an essentially empty CWT (red) and 6 full wing tanks (green). Because the temperature of the wing tanks is dictated by the temperature of the fuel, the wing tanks spend most of a typical flight outside the flammability zone since the fuel is relatively cool. The CWT, on the other hand, spends a substantial portion of the flight within the flammability zone. This is due in part to its proximity to air-conditioning packs, which thermally influence the CWT.

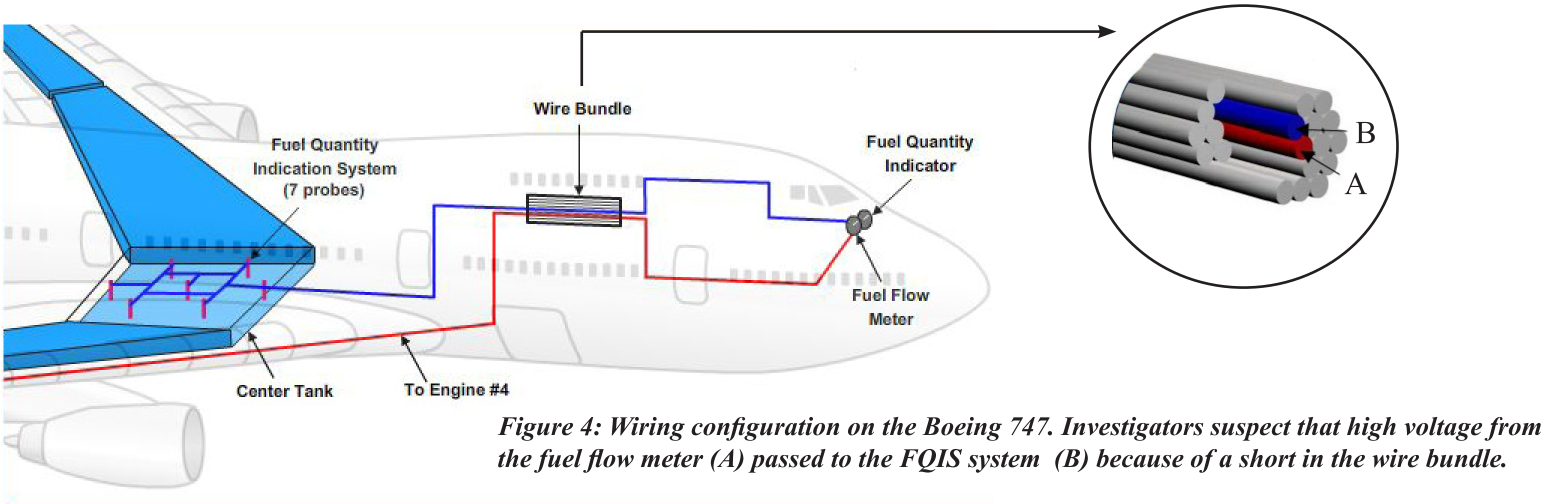

Figure 4: Wiring configuration on the Boeing 747. Investigators suspect that high voltage from the fuel flow meter (A) passed to the FQIS system (B) because of a short in the wire bundle.

wire. The same wire routes were then found to contain other potential electrical energy sources, such as the cabin lights that had been beneath the cockpit. The cabin lights had required maintenance on multiple occasions in the month before the accident. Any of these potential sources could have passed excessive energy to the FQIS system within the CWT (See Figure 4).

UNDERLYING ISSUES

FLAWED ASSUMPTIONS

Fuel tank explosions require both an ignition source and a combustible fuel/air mixture. Because of the pressure and temperature variations that can occur during an airplane's flight, it is difficult to predict the times at which the fuel/air mixture in a tank's ullage is combustible. Prevailing industry practice assumes the mixture is combustible at all times. When designing the 747, engineers relied solely upon eliminating ignition sources to prevent fuel tank explosions. According to the FAA, "it was generally believed that design practices were capable of completely eliminating in-tank ignition sources." This capability depended upon several assumptions: an "explosion-proof" FQIS system, appropriate wire configuration, and sufficiently sensitive circuit breakers. After the accident, investigators realized that a history of fuel tank explosions proved these assumptions invalid. Even after reviewing the designs of all transport airplane fuel systems to the tougher standards that were developed after the accident involving TWA flight 800, known as Special Federal Airworthiness Rule (SFAR) 88, the FAA and industry continued to find that the post SFAR88 review did not identify all potential hazards.

Aging FQIS Components

During qualification testing in the 1960's, FAA examiners found FQIS probes free of arcing up to 2,000 volts and deemed the FQIS system "explosion-proof." After the accident, NTSB investigators tested FQIS components in aircraft that had been in service for more than 30 years - the same length of time the accident airplane had been operating. These examiners observed that silver sulfide deposits had accumulated on the probes – presumably because of their long exposure to jet fuel contaminants. NTSB concluded the semi-conductive nature of this deposit was probably enough to induce an electrical arc inside the CWT at minimal voltage, igniting the fuel vapor and resulting in the subsequent tank explosion.

Investigators also found other conditions from routine service that could lead to potential ignition hazards. For example, drilling conducted as routine maintenance could leave shavings that bridged between the fuel probes and aluminum structure, acting as potential heating filaments when subjected to excessive energy from a short circuit elsewhere in the system.

Although the FQIS system displayed explosion-proof capability at the time of aircraft certification, designers did not account for the effects of aging upon the system. Certified as explosion-proof, the probes were never retested.

Wire Configuration and Maintenance

Like all large aircraft of its era, B-747 design allows circuits from multiple systems to be co-bundled along shared raceways in the fuselage. Designers may have assumed such a layout would not impose mechanical wear on insulation leading to failure, but when NTSB looked at wiring inside both old and new transport aircraft, their findings conclusively proved otherwise. The Board observed wiring whose insulation had been cut, degraded, chafed, or otherwise compromised. They also discovered metal shavings on and between wires bundled together. Fluid that had leaked from the cabin and galleys had accumulated in the wire bays, creating what investigators described as "syrup" that could serve as an electrical conductor. In some cases, the wire bundles were found "adhered into solid, stiff masses." Board-sponsored tests showed fluids that have migrated between wires with cracked or damaged insulation could contact copper conductors and act as mechanisms through which short energy bursts could intermittently transfer. Metal shavings lying on and between wires in bundles could easily cut through insulation and act as bridges to form short circuits between the wires. Per the NTSB, such conditions would allow high voltage to enter FQIS components.

FAA maintenance policy classified aircraft wiring as "on-condition," meaning wiring components were not maintained according to a set schedule, but addressed only when a malfunction or a failure occurred. Maintenance personnel visually inspected wiring only in concurrence with zonal inspections or fuel tank structural inspections. But without extensive, dedicated, and intrusive inspections, problems such as worn wiring or degrading internal FQIS components, corrosion, or debris in wire raceways would go undetected. Because such inspections were not a part of the 747's maintenance schedule, technicians did not identify the latent failures that led to the accident.

Unreliable Circuit Breakers

TWA 800 was equipped with thermally activated circuit breakers. Post-accident testing showed that currents of 2 to 4 joules could transfer between wires for as long as 25 minutes without heating a wire to the level required to trip such a circuit breaker. Based on these tests, NTSB concluded that thermally activated circuit breakers, such as those used on TWA 800, do not function fast enough to reliably prevent excessive energy from entering FQIS wires, as previously assumed. Later, NTSB recommended installing arc-fault circuit breakers and other current limiting devices, instead of simple thermal-mechanical circuit breakers to prevent energy transfers.

Aftermath

In 2001, the FAA issued Special Federal Aviation Regulation (SFAR) 88 which required re-examination of all airplanes with regard to ignition prevention. These reviews utilized the newest standards and knowledge gained through the fuel tank investigation, rather than the earlier standards that existed when airplanes had been certificated. The SFAR also required safety enhancements, such as regular cleansing of silver sulfide deposits from FQIS probes. In 2007, the FAA issued a requirement for aircraft wiring to undergo targeted maintenance. The FAA also recommended improved training for aircraft maintenance personnel since some of the hazards NTSB investigators found when inspecting airplanes similar to TWA 800, such as metal shavings in the wire bays, could be viewed as commonplace and not considered a hazard. Because potential hazards continue to be found, even after the SFAR 88 review, the FAA continues to monitor fuel tank designs and modifications, which continues to result in additional airworthiness directives.

During the course of the NTSB investigation, it became clear that sole reliance upon ignition preventive design was an inadequate means of avoiding a CWT explosion; somehow, the CWT itself had to be rendered incombustible as an additional layer of protection. The military had accomplished this in combat aircraft by using systems to inject inert gas such as nitrogen to displace oxygen in fuel tanks from 21% down to 9%. Such systems had been considered unnecessary in cost and weight by the commercial transport aircraft industry. However, by recognition that commercial airplanes did not need the level of inerting used by the military, the FAA developed a relatively lightweight and simple flammability reduction system (FRS) from advanced inerting system technologies. These developments made retrofitting of commercial aircraft feasible. In 2008, the FAA issued a fuel tank flammability rule requiring airlines to retrofit (within 10 years) a means to reduce the flammability of heated fuel tanks in all Boeing and Airbus aircraft manufactured before 2009. Methods could include systems to displace oxygen in tanks with inert nitrogen, or use of materials to mitigate ignition such as polyurethane foam fill.

For Future NASA Missions

The FAA did not require airlines to schedule targeted inspections and maintenance for the wiring network partly because of the difficulty such inspections would entail. A typical wide-body jet can contain 240 kilometers of wire; accessing those wire harnesses would mean dismantling the aircraft's external structure. Because of this difficulty, problems resulting from aging wiring systems are becoming prevalent in both commercial aircraft and in military fighters. NASA faces similar challenges in its own densely wired systems. NASA's wire networks are equally susceptible to chafing from vibration, breakdown from moisture, or cracking from age. While it may be impractical to dismantle and visually inspect every inch of the wiring labyrinth winding through a spacecraft's recesses, knowing that arcs, shorts, and electromagnetic interference present constant threats to product operation must lead designers to install additional layers of safety to protect against wiring malfunctions. Products still in the concept phase of the project life cycle should account for the effects of age and include a means to later analyze the wire system's integrity.

Questions for Discussion

- What are some of the assumptions you made about your project when it began?
- Have you re-evaluated those assumptions to assess their continued validity?
- How do your maintenance and quality procedures protect your system from the effects of age and wear?
- Have you considered the practicality of implementing additional layers of safety for your system?

When TWA 800 plunged into the Atlantic, certain assumptions that aircraft designers had relied upon for three decades vanished. When FQIS components were new, they had qualitatively and quantitatively proven to be "explosion-proof," but, this assumption was never reassessed, even after the aircraft logged more than 90,000 hours of operation. At NASA, it is critical to continue questioning initial assumptions about operations, equipment, and facilities. Defects that prove to be critical may develop over time, and detecting latent failures is not always easy. Sustaining rigorous maintenance and quality checks underscores recognition that failure modes cannot always be identified at the time of a product's inception. Installing targeted inspection and maintenance practices are critical to product and mission success.

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